Journal of Hydrology 557 (2018) 173–181

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Trends and variability in streamflow and snowmelt runoff timing in the southern Tianshan Mountains

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ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 29 October 2017
Accepted 11 December 2017
Available online 12 December 2017
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Daqing Yang, Associate Editor

Keywords:
Climate change
Winter/spring snowmelt runoff time
WSCT
Tarim basin
Central Asia

ABSTRACT

Streamflow and snowmelt runoff timing of mountain rivers are susceptible to climate change. Trends and variability in streamflow and snowmelt runoff timing in four mountain basins in the southern Tianshan were analyzed in this study. Streamflow trends were detected by Mann-Kendall tests and changes in snowmelt runoff timing were analyzed based on the winter/spring snowmelt runoff center time (WSCT). Pearson's correlation coefficient was further calculated to analyze the relationships between climate variables, streamflow and WSCT. Annual streamflow increased significantly in past decades in the southern Tianshan, especially in spring and winter months. However, the relations between streamflow and temperature/precipitation depend on the different streamflow generation processes. Annual precipitation plays a vital role in controlling recharge in the Toxkon basin, while the Kaidu and Huangshuigou basins are governed by both precipitation and temperature. Seasonally, temperature has a strong effect on streamflow in autumn and winter, while summer streamflow appears more sensitive to changes in precipitation. However, temperature is the dominant factor for streamflow in the glacierized Kunmalik basin at annual and seasonal scales. An uptrend in streamflow begins in the 1990s at both annual and seasonal scales, which is generally consistent with temperature and precipitation fluctuations. Average WSCT dates in the Kaidu and Huangshuigou basins are earlier than in the Toxkon and Kunmalik basins, and shifted towards earlier dates since the mid-1980s in all the basins. It is plausible that WSCT dates are more sensitive to warmer temperature in spring period compared to precipitation, except for the Huangshuigou basin. Taken together, these findings are useful for applications in flood risk regulation, future hydropower projects and integrated water resources management.

1. Introduction

Snowmelt contributes substantially to the springtime runoff and streamflow in mountain regions with colder climates. The timing and volume of snowmelt runoff and streamflow can be particularly sensitive to climate change (Barnett et al., 2005; Stewart et al., 2004; Clow, 2010; Viviroli et al., 2011; Leppi et al., 2012). The rivers flowing from the Tianshan Mountains (known as the "Water tower of Central Asia") are an important freshwater source for Central Asia (Sorg et al., 2012; Chen et al., 2016a,b). Additionally, the snowmelt in the Tianshan Mountains, as in other cold mountain regions, contributes substantially to the springtime runoff and streamflow portions of the regional water balance (Chen et al., 2016b). Average temperature and precipitation have been increasing over recent decades in northwestern China where the Tianshan Mountains are located (Xu et al., 2004; Chen et al., 2006; Kong and Pang, 2012). As precipitation influences streamflow directly, while temperature mainly affects evapotranspiration, snow/glacier melt and the form (rain or snow) of precipitation (Singh and Singh, 2001; Molini et al., 2011); warmer and wetter conditions may result in an accelerated and unstable regional hydrological cycle in this semiarid region (Shen and Chen, 2010; Chen, 2014). Streamflow variability is therefore remarkably important for studying the impacts of climate change.

Streamflow and snowmelt runoff timing in the Tianshan Mountains are expected to change under a changing climate. Streamflow experienced a remarkable increase with climate warming (Chen et al., 2009, 2013; Liu et al., 2011) which-combined with glacier shrinkage-leads to a significant increase in streamflow volume and earlier snowmelt runoff in the Urumqi basin (Sun et al., 2015). According to model simulations, the timing of snowmelt runoff is projected to shift earlier due to temperature increase in spring (Wang et al., 2010; Liu et al., 2011). However, the impacts

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https://doi.org/10.1016/j.jhydrol.2017.12.035
0022-1694/

of climate change on streamflow differ in different basins. The Xinjiang province portion of the Tianshan mountains in China runs from west to east (around 1700 km long), and therefore intercepts moist air coming from the westerlies and results in unevenly distributed precipitation and water resources (Chen, 2014). The northern and western slopes of the Tianshan receive more precipitation than the southern and eastern parts (Xu et al., 2010), while temperature on the southern slopes is higher than on the northern slopes (Shen et al., 2016). The climate-related impacts on streamflow are even more complex in glacierized catchments. For instance, streamflow change in the Kaidu basin in summer is mainly attributed to changes in mountain precipitation (Deng et al., 2015), while temperature dominates streamflow changes in the highly glacierized Kunmalik basin (Kundzewicz et al., 2015). Generally, the distribution of streamflow and snowmelt runoff timing are undergoing significant changes due to climate variability, which motivates the need to identify the streamflow variability and snowmelt runoff timing in meltwater-dependent basins.

Changes in streamflow and snowmelt runoff timing have become evident in other regions in recent decades. Global streamflow has tended to increase in the warming climate (Labat et al., 2004). In addition, streamflow increases have been projected due to increased temperature and precipitation in a glacierized river basin in Nepal (Immerzeel et al., 2012). Quantified by means of center of volume date (CT) and spring pulse onset, streamflow and snowmelt runoff timing were shifted earlier due to temperature increase in New England (Hodgkins et al., 2003) and Colorado (Clow, 2010). These changes are also observed in western North America and Eurasian Arctic rivers (Stewart et al., 2004, 2005; Cayan et al., 2001; Tan et al., 2011). Based on GCM models, the projected streamflow in Quebec, Canada, is expected to increase in winter and decrease in spring (Boyer et al., 2010). Taken together, changes in streamflow and snowmelt runoff timing are important indicators of climate-related changes (Hodgkins et al., 2003). However, climate change and its impacts on streamflow are still poorly described, especially with respect to snowmelt runoff changes in glacierized catchments in the Tianshan Mountains (Chen et al., 2016b). Currently, not much research in the Tianshan Mountains focuses on the streamflow variability at the basin scale, while much of the recent work has focused on large regional areas (Shi et al., 2007; Chen et al., 2009; Tao et al., 2011; Xu et al., 2010; Wang et al., 2013). Therefore, it is not well known how changes in climate might impact streamflow and snowmelt runoff timing in different basins of the Tianshan Mountains. To improve our general understanding of the impacts of climate change, the knowledge of seasonal relationships between hydro-meteorological variables at the basin scale must be improved.

This study therefore seeks to estimate the trends and variability of streamflow and snowmelt runoff timing in four mountain basins in the southern Tianshan (from west to east) and their possible sensitivity to climate change. The objectives are: (1) to estimate annual, seasonal and monthly historical streamflow characteristics in four glacierized basins in the Tianshan Mountains; (2) to characterize possible changes in snowmelt runoff timing; (3) to obtain insights into hydrological processes and to identify the relationships between hydrological changes associated with climate variables.

2. Study area, data and methods

2.1. Study area

Four glacierized basins (Toxkon, Kunmalik, Kaidu and Huangshuigou, respectively) in the southern Tianshan were chosen based on the location and data availability (Fig. 1 and Table 1). Mean elevations of the Toxkon, Kunmalik, Kaidu and Huangshuigou basins are 3634, 3707, 3008 and 2840 m above sea level (a.s.l), respectively. The Toxkon and Kunmalik basins drain approximately 19,166 and 12,816 km^2 upstream from the Shaliguilanke and Xiehela stations (Table 1). They are the main headwater subcatchments of the Aksu River, which is the main tributary of the Tarim basin, accounting for about 80% of its annual streamflow. In addition, approximately 4% and 20% of the Toxkon and Kunmalik basins, respectively, are glacierized (Doris et al., 2016). The Kaidu and Huangshuigou basins are located in the central southern part of the Tianshan Mountains and cover 18,649 and 4298 km^2 upstream from the Dashankou and Huangshuigou gauge stations. Streamflow from the Kaidu and Huangshuigou basins finally arrive at Bosten Lake which is another important water source for the Tarim basin.

The basins are characterized by a continental semiarid climate. Mean annual streamflow in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins are 148, 381, 189 and 69 mm/year, respectively (Table 1). Temperature and precipitation (from APHRODITE, see the Data section) are highly heterogeneous due to large elevational gradients and complex topography. The Kaidu basin has the coldest winters (mean winter temperature −20.4 °C), followed by the Kunmalik (−17.2 °C), Huangshuigou (−15.8 °C) and Toxkon (−15.2 °C) basins (Fig. 2). The highest mean summer temperature is found in the Huangshuigou basin (10.4 °C). Average summer temperatures in the Toxkon, Kunmalik and Kaidu basins are 9.3, 6.9 and 9.2 °C, respectively. Generally, temperature in winter is more variable than in summer, while the opposite holds true for precipitation (Fig. 2). Winter is the driest season for all the basins (15, 23, 11 and 6 mm for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins, respectively). Precipitation mainly occurs in summer (115, 152, 138 and 127 mm for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins). Moreover, average precipitation in spring is higher in the Toxkon and Kunmalik (65 and 79 mm) than the Kaidu and Huangshuigou (37 and 30 mm, respectively) basins.

2.2. Data

Streamflow gauge data were obtained from the Hydrology and Water Resources Bureau of Xinjiang. Four stations with daily streamflow data are available in the Tianshan Mountains. The gauge locations are shown in Fig. 1 and the corresponding summary information is listed in Table 1. The streamflow data cover a period of more than 30 years and all the data were strictly checked for homogeneity. There are a few days of missing data (<1% of the daily values) for the daily streamflow in the Shaliguilanke, Xiehela and Huangshuigou stations. However, monthly data are available. We interpolated the missing data using linear regression with neighboring data. Although uncertainties remain, we assume that they won't have much influence on the trend detection.

There is only one observation station in each basin, which cannot represent the spatial climate for the whole basin. Therefore, time series of mean temperature and precipitation data within these basins were extracted form APHRODITE (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) gridded data (Yatagai et al., 2012). APHRODITE covers time span more than 45 years (1951–2007 for precipitation and 1961–2007 for temperature) and it features a spatial resolution of $0.25^\circ \times 0.25^\circ$. APHRODITE is an interpolated dataset that can provides a basic description for the local climate and has been widely applied in central Asia (Immerzeel et al., 2015; Shea et al., 2015; Krysanova et al., 2015). Climate stations are sparse in the Tianshan Mountains and most of the stations are located in the valley; APHRODITE may therefore underestimate the mountain precipitation due to the

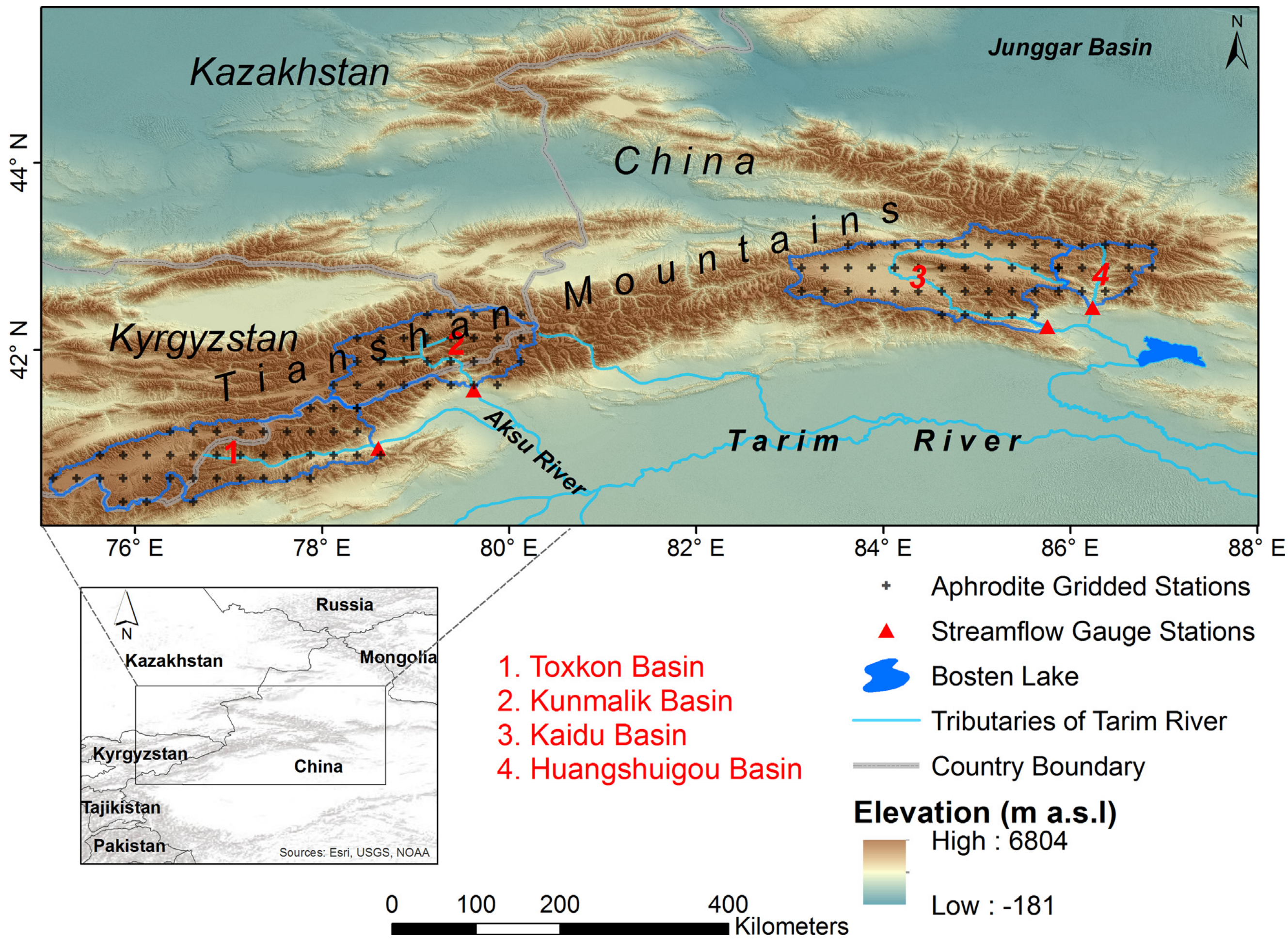

Fig. 1. Location of river basins and gauge stations analyzed in this study.

Table 1
Summary of basins and gauge stations used in this study.

River Basin	Area (km^2)	Gauge Station	Latitude (N)	Longitude (E)	Elevation (m a.s.l)	Data Availability	Annual Streamflow ($m^3\ s^{-1}$)	Annual Streamflow (mm)
Toxkon	19,166	Shaliguilanke	40.95	78.6	2000	1961–2007	89.5	148
Kunmalik	12,816	Xiehela	41.57	79.62	1478	1961–2007	153.7	378
Kaidu	18,649	Dashankou	42.22	85.73	1340	1972–2008	111.2	189
Huangshuigou	4298	Huangshuigou	42.45	86.23	1320	1962–2008	9.3	69

high orographic influence of the Tianshan Mountains. However, in terms of analyzing the streamflow and climate change variability, the trend of climate and their relationship with discharge can also give valuable information. We acknowledge that uncertainties related to the representation of climate in mountain areas remain. The river basins were delineated by using HydroSHEDS elevation data (approx. 90 m × 90 m resolution; Lehner et al., 2008).

2.3. Methods

Temporal trends of streamflow were evaluated using non-parametric Mann-Kendall tests (Mann, 1945; Kendall, 1975) at annual and monthly scales for each basin. Sen's slope (Sen, 1968) was applied to analyze the linear rate of change. To reduce the expected proportion of false discoveries that may occur by chance alone, an adjustment for multiple comparisons was conducted by using the Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995). The false discovery rate was controlled at a level of 0.05, i.e. it is expected that no more than 5% of all null hypotheses rejected in this study were incorrectly rejected. All statistical analyses were performed using R (R Core Team, 2016).

Snowmelt runoff timing was carried out using the theory of "the center of mass of flow" (CT), which is a flow-weighted timing that represents the center of mass of the streamflow curve (Stewart et al., 2004). CT is not necessarily related to the actual snowmelt timing but the change of CT can present as evidence for observed earlier actual melting (Stewart et al., 2005). As most precipitation in the Tianshan Mountains falls in summer, to avoid the impact of large amounts of seasonal rainfall to the flow-weight, we computed CT only for the winter/spring period (January 1st to May 31st) when streamflow is snowmelt dominated. Thus, the annual winter/spring snowmelt runoff center time (WSCT) was calculated from:

$$\mathrm{WSCT} = \sum(t_i q_i) / \sum q_i$$

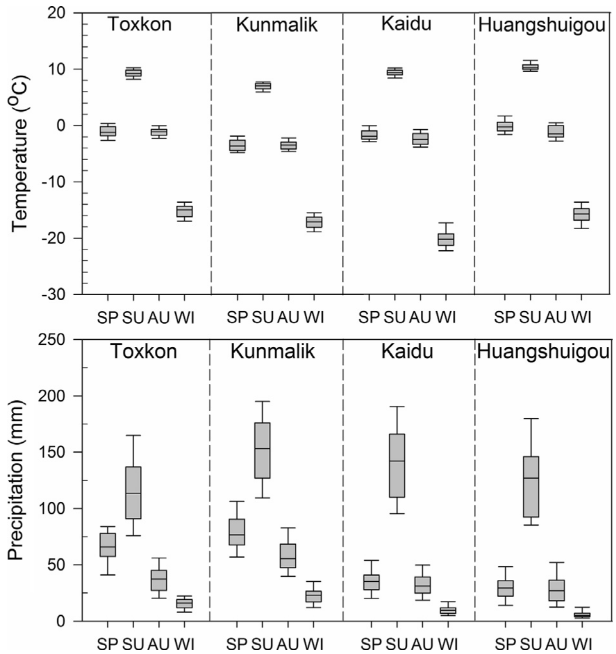

Fig. 2. Boxplots with seasonal normal (1961–2007) of temperature and precipitation for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins in the southern Tianshan. Boxplots represent extreme values, lower and upper quartiles and median value of a variable. Seasons are defined as: SP = Spring (March, April, May), SU = Summer (June, July, August), AU = Autumn (September, October, November), WI = Winter (December, January and February) in this study.

where t_i is time in months (or days) from the beginning of the year (January 1st), q_i is the corresponding streamflow for month i (or day, i). Therefore, WSCT is a date which is given in months or days and smoothed by locally weighted regression (LOESS; Cleveland and Devlin, 1988). The correlations between streamflow, WSCT, temperature and precipitation were furthermore measured using Pearson's correlation coefficient (R).

3. Results

3.1. Trends and variability of streamflow

Annual streamflow showed an increasing trend in four basins in past decades based on the Mann-Kendall test and Sen's slope estimator (9.29, 14.35, 18.02 and 4.34 mm per decade for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins, respectively). However, the streamflow increase was more strongly significant in the winter and spring months (from November to March) in four basins (Table 2, Fig. 4). Seasonally, streamflow amounts of the Toxkon and Kaidu basins appear to increase in every season, while there are no significant trends in streamflow in the Kunmalik and Huangshuigou basins in summer and autumn, respectively.

Annual streamflow is expected to show the largest increase from the mid-1990s for each basin (Fig. 3). Seasonal patterns of streamflow are generally similar to the change patterns of annual streamflow that also increased since the early 1990s in terms of the cumulative anomalies (Fig. 4). However, seasonal changes are more variable in spring than changes for other seasons as well as at the annual scale.

3.2. Streamflow links with temperature and precipitation

Changes in streamflow at annual and seasonal scales can be linked to the variations of temperature and precipitation. Annual temperature increased significantly in all basins (0.2, 0.5, 0.5 °C per decade for the Kunmalik, Kaidu and Huangshuigou basins) except for the Toxkon basin. Seasonally, temperature in autumn and winter has significantly increased in all the basins (Table 3). However, only temperature in the Kaidu basin rose significantly in all the seasons. Precipitation tended to increase in all basins, but with more uncertainty, as a significant trend was only detected in the Huangshuigou basin (Table 3). Winter precipitation increased significantly in all the basins, except for the Toxkon basin. However, annual streamflow increased substantially since the mid-1990s, which very likely coincides with change patterns of annual precipitation and temperature. Annual temperature and precipitation also showed significant positive trends since the 1990s (Fig. 3). Seasonal change patterns of temperature and precipitation were also estimated based on the seasonal cumulative anomaly of temperature and precipitation (Figure S1 and S2 in Supporting Information). We found consistent evidence that seasonal temperature had a steep change after the mid-1990s. However, seasonal precipitation is more variable than temperature.

Average precipitation and temperature were compiled at annual and seasonal scales to identify the relationship between streamflow and climate variables (Table 4). Annual and summer streamflows have a positive relation with precipitation in all the basins, except for the glacierized Kunmalik basin. There has been

Table 2
Trends of streamflow in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins.

	Toxkon (1961–2007)		Kunmalik (1961–2007)		Kaidu (1972–2008)		Huangshuigou (1962–2008)	
	mm/decade	P-value	mm/decade	P-value	mm/decade	P-value	mm/decade	P-value
Jan	0.22	<.01	0.24	<.01	1.51	<.001	0.14	.04
Feb	0.20	<.01	0.23	<.01	0.98	<.001	0.14	.02
Mar	0.20	<.01	0.18	<.01	0.99	<.001	0.20	<.001
Apr	0.55	.14	0.23	.15	0.74	.1	0.24	<.01
May	1.22	.01	0.55	.05	0.34	.62	0.21	.22
Jun	1.49	.09	0.55	.48	−0.39	.66	−0.03	.93
Jul	1.88	<.01	6.49	<.01	2.77	.01	1.21	.1
Aug	0.47	.47	5.30	<.01	3.85	<.01	0.80	.15
Sep	0.84	.02	1.94	.06	2.08	<.01	0.61	.04
Oct	0.55	<.01	0.84	.06	1.32	<.01	0.40	<.01
Nov	0.35	<.01	0.36	.02	1.60	<.001	0.27	<.01
Dec	0.28	<.01	0.25	.02	1.49	<.001	0.28	<.01
Annual	9.29	<.001	14.35	<.001	18.02	<.02	4.34	0.03
Spring	1.94	<.01	0.91	<.01	2.11	.045	0.75	<.01
Summer	4.23	<.01	10.43	<.01	6.04	.03	1.97	.19
Autumn	1.71	<.01	2.86	.09	5.43	<.001	1.33	.01
Winter	0.72	<.001	0.60	<.001	4.08	<.001	0.57	<.01

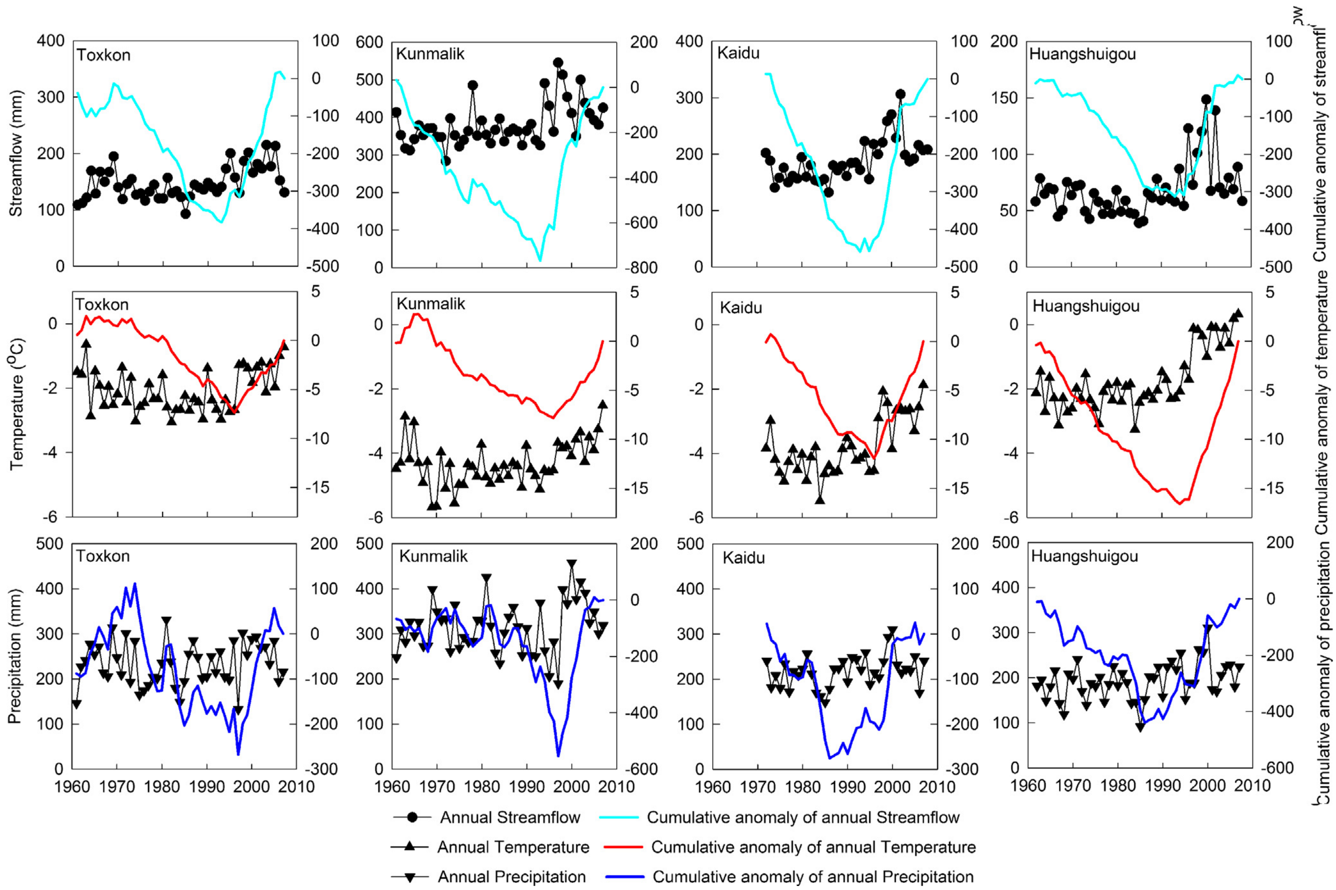

Fig. 3. Annual and cumulative anomalies of streamflow, temperature and precipitation in the Toxkon (1961–2007), Kunmalik (1961–2007), Kaidu (1972–2007) and Huangshuigou (1962–2007) basins. The panel scales for streamflow are different among basins.

no consistent relationship between streamflow and precipitation in the other seasons. Temperature has a significant positive relation with autumn and winter streamflow in the Toxkon, Kaidu and Huangshuigou basins. However, streamflow in the glacierized Kunmalik basin generally has a significant relationship with temperature at annual and seasonal scales.

3.3. Changes of snowmelt runoff timing

Long-term changes in WSCT showed no significant trend based on the Mann–Kendall tests, except for the Kaidu basin (−3.4 days/decade, p < .01), whose significant negative trend may have been enhanced by the short data period. From west to east, WSCT shifts towards earlier dates. Average WSCT during the study period for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins are Julian day 111, 98, 94 and 87, respectively. A general nonlinear pattern was apparent according to which the WSCT dates rose first and then decreased after mid-1980s based on the loess smooth line (Fig. 5). All the gauge stations show consistent fluctuations in WSCT, which indicates earlier snowmelt runoff timing and increased winter/spring runoff (Table 2). WSCT shifted toward earlier dates after the mid-1980s: 11 days (Julian day range: 103–114) in the Toxkon basin, 5 days (94–99) in the Kunmalik basin, 8 days (88–97) in the Kaidu basin, and 8 days (82–90) in the Huangshuigou basin, respectively.

3.4. Relations of WSCT to temperature and precipitation

Changes in WSCT may be additional indicators of changing precipitation and temperature. Rivers that originate from the Tianshan Mountains are mainly supplied by precipitation and meltwater from snow and glaciers; correlations between monthly precipitation and temperature with WSCT dates were therefore explored (Table 5). There was no significant relationship between WSCT dates and precipitation in the Toxkon basin. However, average precipitation was found to have weak but significant positive correlation with WSCT dates in May (r = 0.39, p = .02) in the Kaidu basin and in March (r = 0.37, p = .01) in the Huangshuigou basin. Nevertheless, the strongest correlation between WSCT dates and temperature in the Toxkon basin was found in the period of February to April (r = −0.46, p < .01). The strongest correlation between WSCT dates and temperature in the Kaidu basin was found in the period of March to April (r = −0.66, p < .001); while no significant relationships were found in the Huangshuigou basin. However, WSCT dates were found to have a negative relationship with precipitation in the period of January to April (r = −0.34, p = .02) and a positive relationship with temperature in May (r = 0.59, p < .001) in the Kunmalik basin.

4. Discussion

The relationships between streamflow on the one side and temperature and precipitation on the other side vary among the basins at annual and seasonal scales, which may be due to different streamflow generation processes. Basins in mountain areas are mainly recharged by both precipitation and meltwater, as is the case in the Kaidu and Huangshuigou basins (Zhou et al., 2016). However, large amounts of precipitation are stored in the form of snow or glaciers. In the strongly glacierized Kunmalik basin,

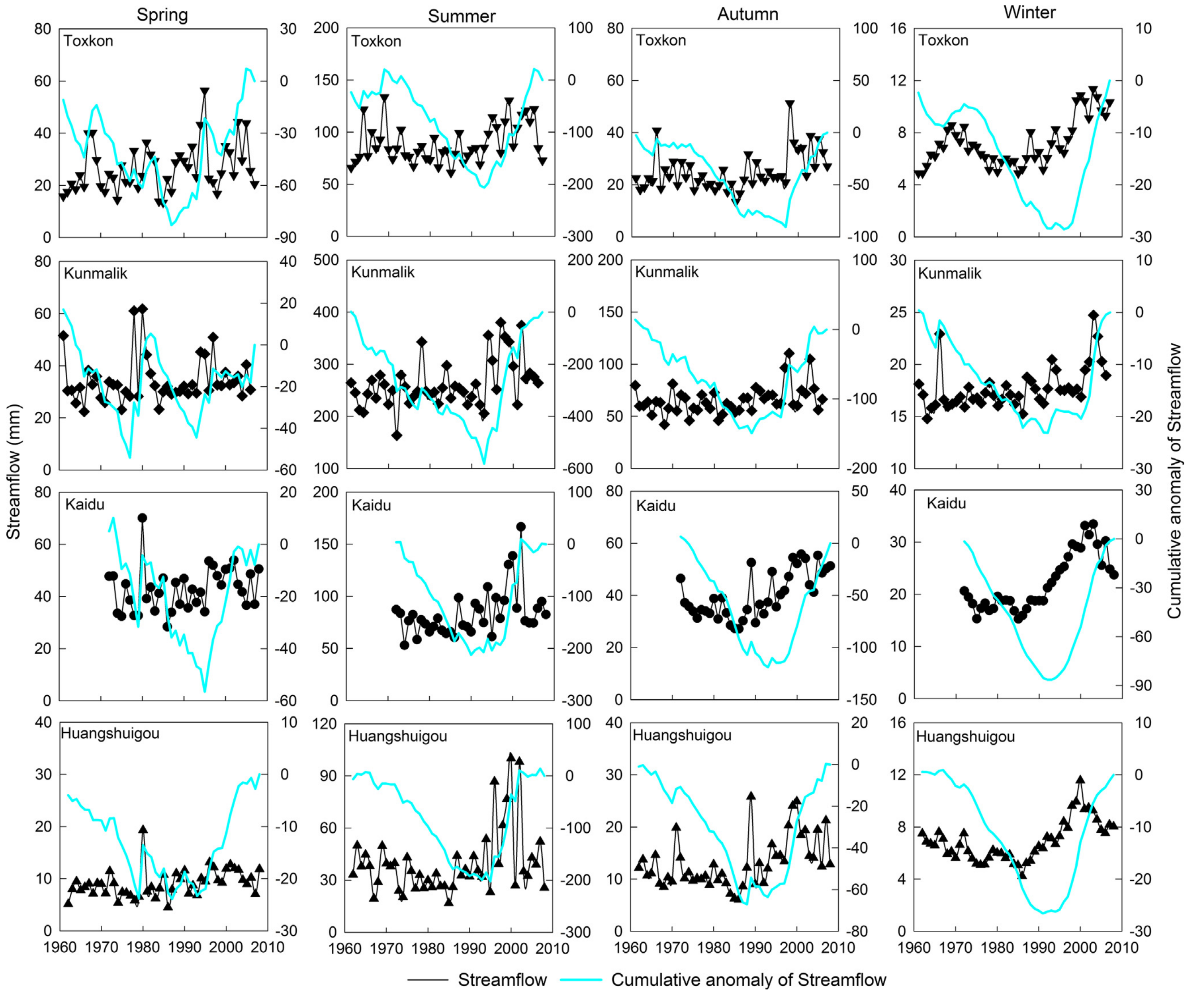

Fig. 4. Seasonal and cumulative anomalies of streamflow in the Toxkon (1961–2007), Kunmalik (1961–2007), Kaidu (1972–2008) and Huangshuigou (1962–2008) basins. The panel scales are different for each basin in different seasons.

Table 3
Trends of precipitation and temperature in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins.

Time period	Toxkon (1961–2007)				Kunmalik (1961–2007)				Kaidu (1972–2007)				Huangshuigou (1962–2007)			
	Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature	
	mm/decade	P-value	°C/decade	P-value	mm/decade	P-value	°C/decade	P-value	mm/decade	P-value	°C/decade	P-value	mm/decade	P-value	°C/decade	P-value
Annual	5.0	.37	0.1	.28	8.2	.26	0.2	.01	10.3	.07	0.5	<.001	10.9	.01	0.5	<.001
Spring	0.3	.87	−0.2	.23	3.4	.20	−0.1	.46	−0.7	.69	0.5	.02	−0.6	.58	0.3	.06
Summer	0.9	.84	−0.1	.47	−1.8	.66	0.1	.26	10.3	.08	0.4	<.001	8.2	.02	0.3	<.001
Autumn	2.2	.15	0.2	.02	3.6	.05	0.3	.01	−0.6	.82	0.6	<.01	0.00	1.00	0.6	<.001
Winter	0.4	.57	0.3	.02	2.1	.04	0.4	<.01	1.7	<.01	0.7	<.01	0.9	<.01	0.8	<.001

streamflow is therefore highly dependent on temperature controlled snow and glacier meltwater (Krysanova et al., 2015; Kundzewicz et al., 2015; Doris et al., 2016). The Toxkon basin has less glacier area and relatively lower elevation compare to the Kunmalik basin, which leads to a faster response of streamflow to precipitation (Krysanova et al., 2015; Kundzewicz et al., 2015). Precipitation accumulated in winter as snow will be released as meltwater in the later warmer months. Thus, increased winter precipitation and temperature can possibly explain the positive trends in streamflow in winter and spring (Tables 3 and 4). Nevertheless, owing to high glacier coverage in the Kunmalik basin, streamflow is generally more affected by temperature variability in any season.

Streamflow increased more obviously in these four basins after the 1990s, which further confirmed that streamflow is highly affected by the warmer temperature and higher precipitation in this period. This result is consistent with previous research (Chen

Table 4
Correlation coefficients between streamflow and average precipitation/temperature in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins.

Time period	Toxkon (1961–2007)				Kunmalik (1961–2007)				Kaidu (1972–2007)				Huangshuigou (1962–2007)			
	Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature	
	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value
Annual	0.49	<0.001	0.07	0.66	−0.02	0.83	0.35	.02	0.57	<.001	0.60	<.001	0.59	<.001	0.52	<.001
Spring	0.19	0.19	−0.23	0.13	−0.04	0.77	0.35	.02	0.50	<.01	−0.03	.86	0.13	.40	0.07	.65
Summer	0.42	<0.01	−0.07	0.63	−0.24	0.09	0.47	<.001	0.46	<.01	0.26	.12	0.56	<.01	0.15	.31
Autumn	0.45	<0.001	0.37	0.01	−0.01	0.94	0.38	<.01	0.17	.31	0.61	<.001	0.23	.12	0.51	<.001
Winter	−0.04	0.80	0.32	0.02	0.18	0.21	0.14	.345	0.38	.02	0.54	<.001	0.29	.05	0.62	<.001

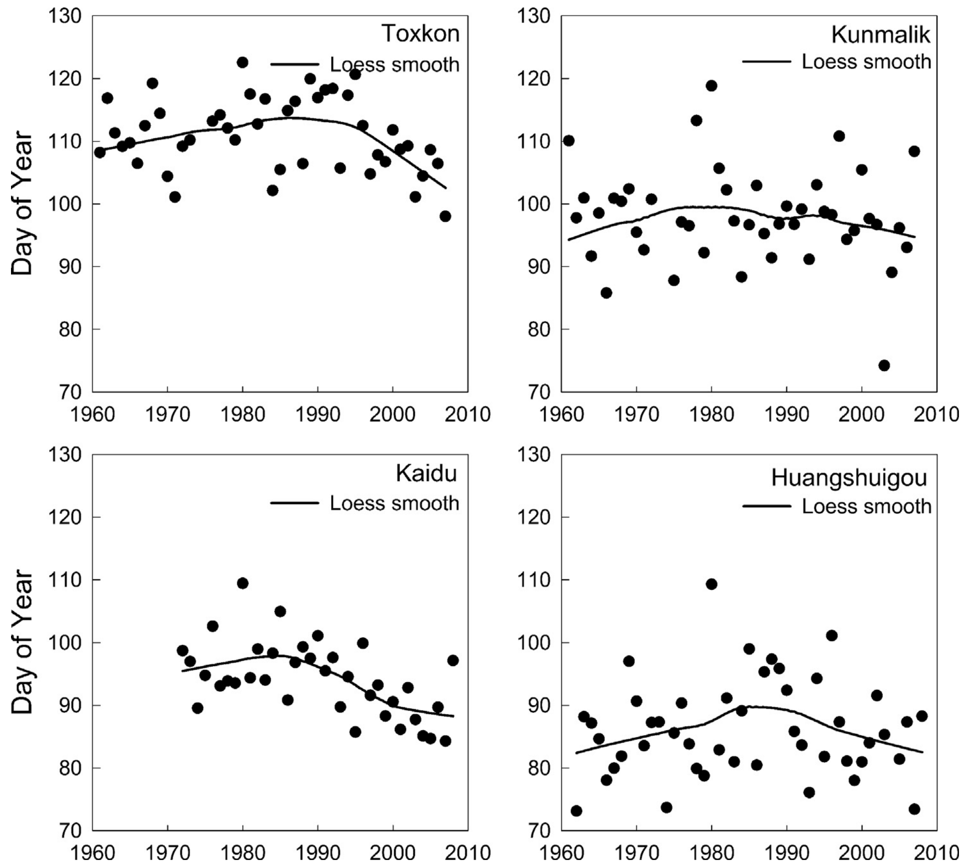

Fig. 5. Time series of historical WSCT in the Toxkon (1961–2007), Kunmalik (1961–2007), Kaidu (1972–2008) and Huangshuigou (1962–2008) basins.

Table 5
Correlation coefficients between WSCT dates and average precipitation/temperature in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins.

Time period	Toxkon (1961–2007)				Kunmalik (1961–2007)				Kaidu (1972–2007)				Huangshuigou (1962–2007)			
	Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature		Precipitation		Temperature	
	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value	R	P-value
Jan	0.13	.37	−0.21	.16	−0.15	.31	−0.05	.73	−0.19	.26	−0.23	.18	0.07	.62	−0.12	.42
Feb	−0.03	.82	−0.36	.01	−0.40	.01	−0.16	.29	0.10	.56	−0.27	.11	−0.04	.80	−0.13	.38
Mar	0.04	.80	−0.16	.28	−0.15	.31	0.03	.83	0.27	.11	−0.64	<.001	0.37	.01	−0.12	.42
Apr	0.14	.36	−0.42	<.01	−0.20	.19	0.31	.03	0.11	.51	−0.43	<.01	0.03	.86	0.06	.70
May	0.08	.59	0.01	.96	0.07	.63	0.59	<.001	0.39	.02	−0.23	.19	0.09	.54	0.19	.20
Jan to Mar	0.05	.72	−0.36	.01	−0.30	.04	−0.09	.53	0.11	.52	−0.45	<.01	0.29	.05	−0.16	.30
Jan to Apr	0.14	.36	−0.45	<.01	−0.34	.02	0.03	.85	0.14	.41	−0.52	<.01	0.19	.21	−0.11	.45
Feb to Mar	0.02	.91	−0.36	.01	−0.29	.05	−0.09	.53	0.24	.16	−0.49	<.01	0.31	.03	−0.15	.31
Feb to Apr	0.12	.44	−0.46	<.01	−0.33	.02	0.06	.71	0.22	.20	−0.58	<.001	0.19	.21	−0.10	.53
Mar to Apr	0.14	.37	−0.36	.01	−0.25	.09	0.21	.16	0.22	.20	−0.66	<.001	0.20	.18	−0.04	.81
Mar to May	0.15	.30	−0.27	.07	−0.11	.46	0.36	.01	0.41	.01	−0.64	<.001	0.19	.2	0.04	.78

et al., 2009; Xu et al., 2010; Tao et al., 2011; Wang et al., 2013). The atmospheric water vapor content, which increased in the 1990s, together with the intensified water cycle caused by global warming could further have strengthened the streamflow variability (Shi et al., 2007; Chen et al., 2008). However, the mechanisms behind the abrupt changes need further research.

Changes in snowmelt runoff timing provide another indication that streamflow are susceptible to climate fluctuation in the Tianshan Mountains. Average snowmelt runoff timing in the western basins is later than in the eastern basins. This finding may demonstrate that the Toxkon and Kunmalik basins are more influenced by the westerlies (Chen, 2014), while the Kaidu and Huangshuifou basins are located in central Xinjiang where the climate is warmer and dryer (Fig. 2). The changes of WSCT dates are coherent in all the basins; snowmelt runoff timing shifted towards earlier dates since the mid-1980s. Since these basins are not heavily influenced by human activities, the substantial changes of WSCT could be primarily driven by the changes of precipitation and temperature. A break point of temperature change was also identified in the mid-1980s (Chen et al., 2006, 2007; Xu et al., 2010).

The association of WSCT with temperature and precipitation in different periods in the Toxkon and Kaidu basins indicated that WSCT happens earlier when spring temperature is higher. Meanwhile, significant correlations of temperature are generally stronger than the precipitation correlations, which further confirms that WSCT is more sensitive to temperature variability. This finding is consistent with previous studies, according to which the changes of spring streamflow are related to the spring temperature change (Liu et al., 2011; Zhuang et al., 2015). However, precipitation is weakly but positively correlated with the WSCT. Precipitation accumulated in spring will lead to greater snow depth and longer snow cover duration, which will lead to a later meltwater peak in the warm months; the snowmelt runoff center time therefore will be delayed. WSCT in the Huangshuigou basin did not have a significant relationship with temperature, which could be explained by its small area and relatively lower elevation reducing the importance of snowmelt. The Kunmalik basin has a highly snow cover and glaciers extent, which may be the reason for a stronger relationship between streamflow and temperature but poor relationship with precipitation. Previous study had already indicated that the spring streamflow is dominated by changes in temperature (Kundzewicz et al., 2015).

Streamflow runoff changes presumably reflect a complex response to climate change. However, uncertainties remain. The process of snow and glacier melt is a complex issue in terms of orographic effects and data availability in mountain regions. In addition, data length, quality and analysis methods are also contribute to uncertainties in the estimation. Furthermore, since discharge data for artificial reservoirs was not available; the investigation of snowmelt and hydrological changes may be biased in the Kaidu basin. Even though the two reservoirs (Dashankou and Chahanwusu) have small capacity (5.8% of the annual streamflow) since 1992, they can still influence streamflow during the dry season. However, the positive trend and presence of a break point are comparable to the adjacent Huangshuigou basin.

Mountain basins shoulder the task of suppling fresh water for downstream rivers. Since streamflow is substantially influenced by the variability of climate and climate change, the variability of streamflow and snowmelt runoff timing can be important indicators for climate change. Additionally, snowmelt runoff shifted earlier which may lead to less water released in summer when irrigation water demand is high; the changes of streamflow and snowmelt runoff timing could therefore threaten seasonal water availability (Shen et al., 2013). Furthermore, streamflow in spring and summer is expected to increase in the near future in the Tianshan Mountains (Hagg et al., 2007); and fresh water supply is expected to be pushed towards its limits in the future in northwestern China (Guo and Shen, 2016). This study gives important insights into the spatial variability of streamflow and snowmelt runoff timing, which is of great significance for flood control, hydropower plants adaption and integrated water resources management under the changing climate. In the future, enhanced climate and streamflow observations are required and more comprehensive studies of the impacts of climate change on streamflow in the Tianshan regions based on hydrological modelling are an important next step.

5. Conclusion

Our study provides a comprehensive overview of streamflow variability and snowmelt runoff timing in four mountain basins in the southern Tianshan. Annual streamflow in this area exhibits a significant positive trend in all basins. Seasonally, streamflow mainly increased in winter and spring months. The relationships between streamflow and climate variables revealed that temperature plays a great role on streamflow in autumn and winter, while streamflow is dominated by precipitation in summer in the Toxkon, Kaidu and Huangshuigou basins. The glacierized Kunmalik basin shows a different behavior in which temperature plays a key role for streamflow variability at annual and seasonal scales. Streamflow had an abrupt change in the mid-1990s at annual and seasonal scales, a pattern that can also be identified in precipitation and temperature data from the southern Tianshan. The analysis of winter/spring snowmelt runoff center time has shown that average WSCT dates in the Kaidu and Huangshuigou basins are earlier than in the Toxkon and Kunmalik basins. A clear shift towards earlier WSCT was found since the mid-1980s, which reflects the combined influences of temperature and precipitation. It is particularly noteworthy that WSCT is negatively related to temperature but positively related to precipitation in spring. However, the opposite relationship between WSCT and temperature/-precipitation was found in the glacierized Kunmalik basin. Although uncertainties remain, this study is essential to understanding the variability of streamflow and its relationship with climate variables. Besides, it is distinctly important for regional water resources management. Streamflow variability and snowmelt runoff change in semiarid mountain basins still require further attention.

Acknowledgments

This research was supported by the National Natural Science Foundation of China [41630859] and the Key Project of Chinese Academy of Sciences [KZZD-EW-12-1]. China Scholarship Council (CSC) is acknowledged for the PhD scholarship awarded to the first author. The authors wish to thank Jason Goetz for his constructive comments on the manuscript. We appreciate the editor and anonymous reviewers for their constructive comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2017.12.035.

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